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by David E. Brewe, Herbert W. Scibbe, and William J. Anderson

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SUMMARY

Seven self-lubricating retainer materials (a laminated glass cloth with polytetrafluoroethylene (PTFE) binder, a glass-fiber - molybdenum disulfide-filled PTFE, a glass-fiber-filled PTFE, a bronze-filled PTFE, a copper - PTFE - tungsten diselenide composite, a silver - PTFE - tungsten diselenide composite, and a molybdenum disulfide-filled polyimide) were evaluated in 40-millimeter-bore ball bearings operating in hydrogen gas at 60° R (33° K). The bearings were operated at 20 000 rpm with a 200-pound (890 N) thrust load for total times to 10 hours. Individual bearing runs were of approximately 2-hour durations.

The formation and subsequent life histories of the transfer films were studied and evaluated from highly magnified profile traces of the bearing inner-race grooves. The wear and mechanical integrity of the retainer materials were determined by visual observations and weight-differential measurements after each 2-hour run.

Transfer films on the inner-race ball tracks were maintained for the entire series of runs in the bearings equipped with glass-fiber-filled and bronze-filled PTFE retainers. This transfer film prevented any inner-race wear in these bearings. The laminated glass cloth with PTFE binder material initially provided a substantial transfer film. With continued running, however, the film wore away and steady wear of the inner race began. After 10 hours running, the maximum race wear was 210 micro-inches (5.33×10^{-4} cm) in one region of the ball track. The high race wear was attributed to abrasion by glass particles worn away from the retainer material. Retainer wear of the filled and the laminated glass-cloth PTFE materials was generally less than 0.25 weight percent for the entire series of test runs. Although the metal composites and filled polyimide materials demonstrated film-transfer capabilities to some degree, their high wear rates indicated that they were not suitable candidates for retainer materials in this application.

INTRODUCTION

Rolling element bearings have operated successfully in cryogenic fluids such as liquid hydrogen, liquid oxygen, and liquid nitrogen. The bearing operating conditions in these cryogenic environments have varied from (1) very high speeds with light to heavy loads for several minutes duration, as in rocket engine turbopumps, to (2) moderate speeds and loads for several hundred hours, as in cooling-system pumps (ref. 1). The bearings in these applications are cooled by direct contact with the cryogenic fluid. The bearing-load carrying surfaces are lubricated by the retainers, which are fabricated from self-lubricating materials.

Several investigators have successfully operated ball bearings with self-lubricating retainers for short time periods in liquid hydrogen at DN values (bearing bore in mm times shaft speed in rpm) to 1.6 million, and in liquid oxygen at DN values to 1.2 million (refs. 2 to 4). In another investigation, 10-millimeter-bore ball bearings running at low speed (3150 rpm) in liquid nitrogen successfully completed 1000 hours of operation (ref. 5). The bearing retainers used in the investigations of references 2 to 5 were fabricated from polytetrafluoroethylene (PTFE)-containing materials.

Results of 10-hour wear-screening tests in liquid hydrogen at an equivalent DN value of 4 million have indicated that, in addition to PTFE, other materials, such as metal-based composites and filled polyimide compositions, may have potential as high-speed bearing retainers (ref. 6).

The lubricating mechanism of bearings operating in liquid oxygen or liquid hydrogen consists primarily in the provision of a low shear-strength film on the bearing surfaces to maintain surface integrity and prevent welding. Because of the high contact stresses, the ball-race contacts are the most critical areas. In reference 3, ball bearings were operated in liquid oxygen; surface oxides were formed at the ball-race contacts in addition to the transfer films provided by self-lubricating, filled PTFE retainers. Operation in liquid hydrogen is considerably more difficult because initial oxide films present on the bearing surfaces cannot be reformed in the reducing environment once they have been worn away. Lubrication must therefore be provided solely by transfer films from a self-lubricating retainer. The film-transfer process is illustrated in figure 1. As the bearing rotates, the balls rub against the retainer. Thin films of retainer material are transferred to the balls and subsequently to the race grooves. The retainer locating surface on one of the races is lubricated directly by sliding contact with the retainer material.

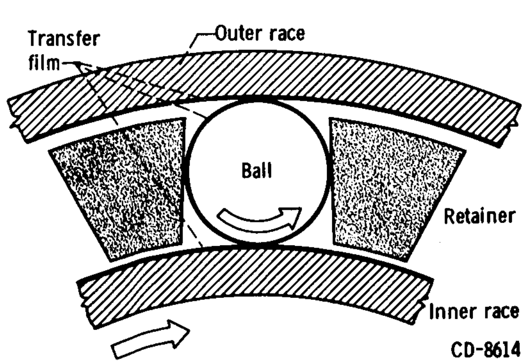


Figure 1. - Film transfer mechanism.

The objectives of this investigation are (1) to determine the film-transfer capabilities of self-lubricating retainer materials by measurement of the film thickness on the bearing race grooves, (2) to evaluate the formation and subsequent life histories of the transfer films, (3) to evaluate the wear characteristics of the retainer materials, and (4) to evaluate the mechanical integrity of the retainers.

Experiments were conducted with 40-millimeter-bore ball bearings operating in 60° R (33° K) gaseous hydrogen at 20 000 rpm with a 200-pound (890 N) thrust load for total running times up to 10 hours. Seven different retainer materials were included in the program: (1) a laminated glass cloth with PTFE binder, (2) a glass-fiber - molybdenum disulfide-filled PTFE, (3) a glass-fiber-filled PTFE, (4) a bronze-filled PTFE, (5) a copper - PTFE - tungsten diselenide composite, (6) a silver - PTFE - tungsten diselenide composite, and (7) a molybdenum disulfide-filled polyimide.

The extent of film transferred into the race grooves was studied by an examination of highly magnified profile traces at run intervals of approximately 2 hours. This technique yielded a history of the buildup and deterioration of the films, and an appraisal was made of the wear resistance of the different materials at the test operating conditions.

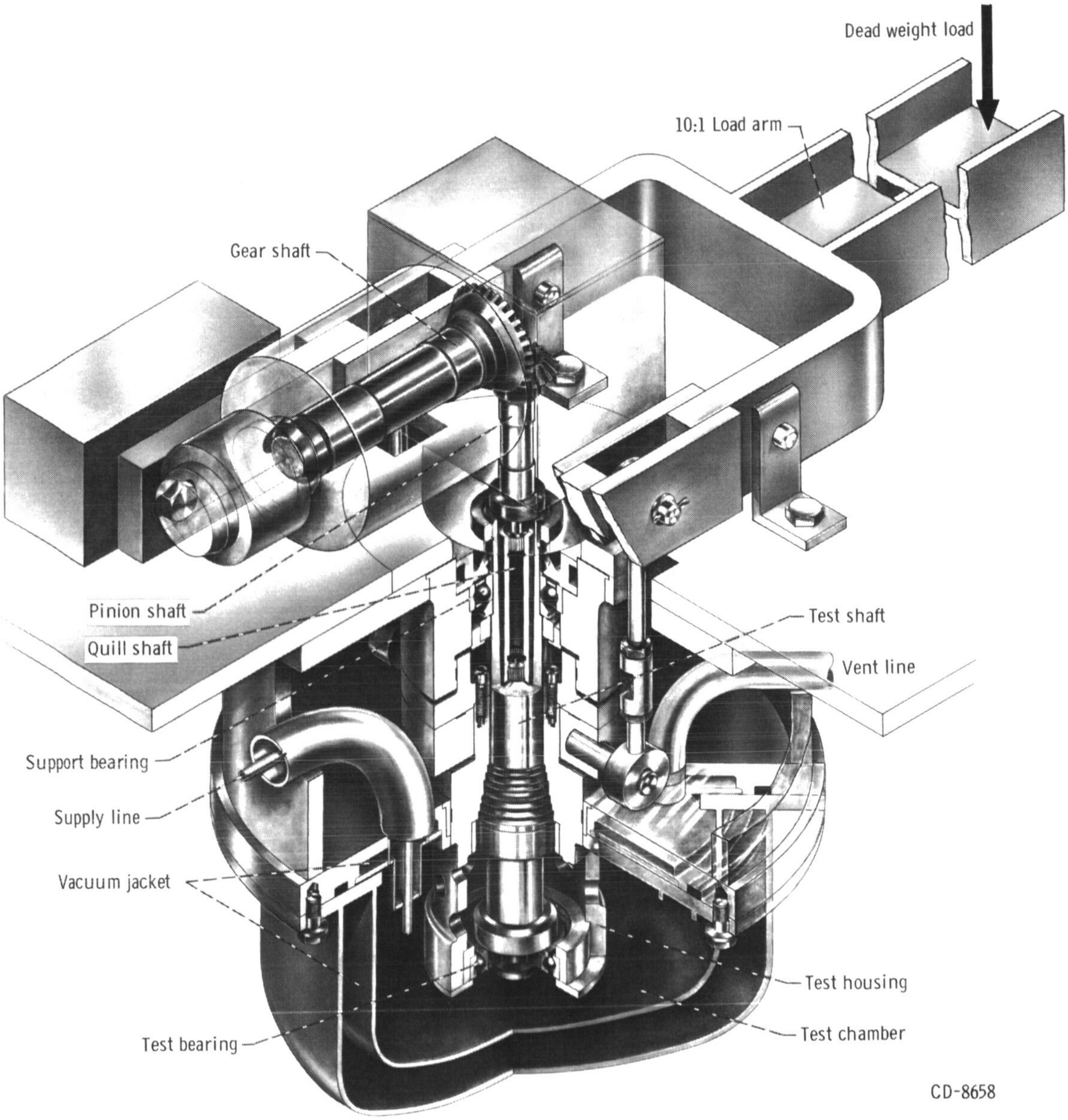
APPARATUS

Bearing Test Rig

The test apparatus shown in figure 2(a) is initially described in reference 2. The test bearing is driven through a gear assembly by a variable-speed direct-current motor. Automatic speed control can be provided over a range of test-shaft speeds from 900 to 52 500 rpm. The test shaft was supported at its lower end by the test bearing and at its upper end by a ball bearing. Thrust load was applied to the test-bearing housing from a deadweight load (fig. 2(a)). A schematic of the test-bearing mounting and support housing is shown in figure 2(b).

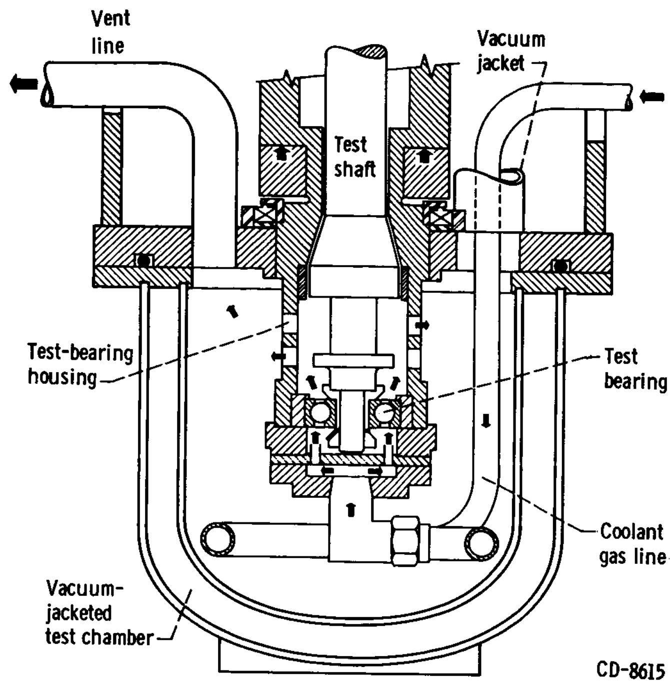
Hydrogen Supply and Exhaust System

The test bearing was cooled by a direct stream of hydrogen gas (fig. 2(b)) from a self-pressurized liquid-hydrogen Dewar. A schematic of the bearing coolant flow system is shown in figure 3. The liquid hydrogen from the Dewar was vaporized to the desired gaseous phase in a shell-tube-type heat exchanger. Hydrogen gas at ambient temperature counterflowing in the shell of the heat exchanger was utilized as the vaporizing agent.



(a) Load system and test shaft mounting.

Figure 2. - Cryogenic fuel bearing test rig (ref. 2).



(b) Schematic of test-bearing mounting and coolant-gas supply.

Figure 2. - Concluded.

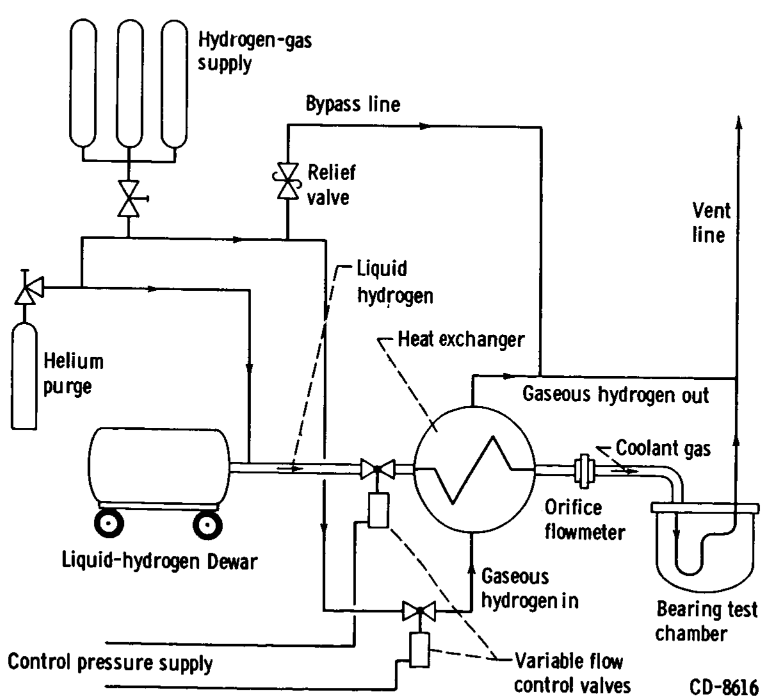


Figure 3. - Schematic of test-bearing coolant flow system.

The cryogenic hydrogen-gas flow to the test bearing was measured by an orifice flowmeter located in the coolant-gas supply line downstream from the heat exchanger. The flow range was from 0.014 to 0.031 pound per second (0.006 to 0.014 kg/sec). After flowing through the test bearing, the coolant gas was exhausted from the test chamber through the vent line. Both the liquid-hydrogen flow from the Dewar and the warm hydrogen-gas flow to the heat exchanger were regulated by remote-control variable-flow valves. The locations of these valves are shown in figure 3. The test chamber, coolant-gas supply line, and liquid-hydrogen line were vacuum-jacketed, whereas the vent and hydrogen-gas lines to the heat exchanger were insulated with 1/2-inch-thick (1.27 cm) polyurethane.

Temperature Measurement

Copper-Constantan thermocouples were used to measure cyrogenic temperatures at the following locations: (1) against the test-bearing outer race, (2) in the coolant-gas supply line downstream from the orifice flowmeter, (3) in the vent line adjacent to the bearing test chamber, and (4) in the inlet and outlet lines of the heat exchanger for both liquid and gaseous hydrogen. Temperature variations within the sensitivity limits of the copper-Constantan thermocouples located in the cryogenic environment were not considered significant for this application. Additional thermocouples were located in the support-bearing housing and in the gearbox housing in the region of the high-speed shaft.

Test Bearings and Retainers

The bearings used in these tests were 40-millimeter-bore (108 series) deep-groove bearings manufactured to ABEC-5 tolerances. One shoulder on the outer race was relieved to make the bearings separable. The inner- and outer-race curvatures were 0.54, and the average radial clearance was 0.0025 inch (0.0064 cm). The ball and race materials were AISI 440C stainless steel.

Bearings 1-S to 10-S were used in preliminary tests, whereas bearings 11-S to 23-S comprised the actual test bearings. The seven retainer materials investigated were the following: (1) laminated glass cloth with PTFE binder, (2) glass-fiber - molybdenum disulfide-filled PTFE, (3) glass-fiber-filled PTFE, (4) bronze-filled PTFE, (5) copper - PTFE - tungsten diselenide composite, (6) silver - PTFE - tungsten diselenide composite, and (7) molybdenum disulfide-filled polyimide. All retainers were inner-race located. The construction, materials, and clearances of the retainers are listed in table I.

TABLE I. - TEST-BEARING RETAINERS

[Deep-groove ball bearings, 40-mm bore, separable at outer race; races and balls, AISI 440C stainless steel; number of balls, 10; ball diameter, 0.375 in. (0.953 cm); inner- and outer-race curvature, 0.54; radial clearance, 0.0025 in. (0.0064 cm).]

Retainer	Approximate weight percent of materials	Retainer construction	Bearing	Inner land clearance		Ball pocket clearance	
				in.	cm	in.	cm
1	38 Percent glass cloth laminates with 62 percent PTFE binder[a]	One-piece body with riveted aluminum side plates	13-S	0.018	0.046	0.019	0.048
			16-S	0.017	0.043	0.015	0.038
2	15 Percent glass fibers, 5 percent molybdenum disulfide, 80 percent PTFE[a]	One-piece body with no external support	14-S	0.031	0.079	0.014	0.036
			23-S	[b]0.048	[b]0.122	0.018	0.046
3	15 to 20 Percent glass fibers, balance PTFE[a,c]	One-piece body with one-piece riveted aluminum shroud	15-S	0.035	0.089	0.016	0.041
			22-S	0.035	0.089	0.026	0.066
4	30 Percent bronze powder, 70 percent PTFE[a]	One-piece body with no external support	20-S	0.038	0.097	0.018	0.046
			21-S	[d]0.019 to 0.066	[d]0.048 to 0.168	0.016	0.041
5	78 Percent copper, 9 percent PTFE, 13 percent tungsten diselenide[e]	Shrink-fit one-piece stainless-steel shroud over one-piece body pinned in two places 180° apart	17-S	0.027	0.069	0.015	0.038
6	85 Percent silver, 5 percent PTFE, 10 percent tungsten diselenide[e]	Same as retainer 5 material without 2 pins	11-S	0.024	0.061	0.015	0.038
		Same as retainer 5 material	18-S	0.025	0.064	0.015	0.038
7	85 Percent polyimide, 15 percent molybdenum disulfide[a]	Shrink-fit one-piece aluminum shroud over one-piece body	12-S	0.022	0.056	0.016	0.041
		Shrink-fit one-piece aluminum shroud over one-piece body with 2 pins 180° apart	19-S	0.019	0.048	0.016	0.041

[a]Manufacturer's data.
[b]Machined to this clearance after running one test with 0.023-in. (0.058 cm) clearance.
[c]Less than 1 percent ferric oxide added as coloring agent.
[d]Inner diameter of retainer machined eccentric.
[e]Metal composites weight percent calculated from measured specific gravity values.

PROCEDURE

Pretest Procedure

The bearings were prepared for testing in the following manner: they were (1) degreased with trichloroethylene, (2) inspected and measured for clearances (transverse surface profiles of the inner- and outer-race grooves were made with the surface profile measuring instrument), (3) washed in trichloroethylene, (4) stored in a vacuum-desiccator chamber for approximately 6 hours, and (5) removed from the desiccator, separated into components, and the individual components weighed prior to testing.

Test Procedure

After the test bearing was installed in the test housing, the coolant-gas supply line, test chamber, vent line, and hydrogen-gas and liquid-hydrogen lines to the heat exchanger were purged for 15 minutes with helium gas. After the purge operation, cold hydrogen gas was force-fed to the bearing. The test shaft was rotated at 900 rpm during the cool-down period. After a cool-down time of approximately 15 minutes, a 200-pound (890 N) thrust load was applied, and the bearing and shaft speed was increased to 20 000 rpm (in 5000 rpm increments every 5 minutes). The 200-pound (890 N) thrust load resulted in maximum Hertz stresses of 230 000 and 213 000 pounds per square inch (1.585×10^9 and 1.465×10^9 N/m^2) for the inner and outer races, respectively.

In the period of operation, the test-bearing outer-race temperature normally ranged from 0° to 12° R (0° to 6.6° K) higher than the coolant-gas temperature. In the event the outer-race temperature increased to more than 12° R (6.6° K) above that of the coolant gas, the flow to the bearing was increased. Therefore, the coolant-gas temperature was maintained at a constant 60° R (33° K). Bearing tests were terminated when the rise in outer-race temperature could not be stabilized by increasing coolant-gas flow. The flow range of coolant gas supplied to the test bearing was from 0.014 to 0.031 pound per second (0.006 to 0.014 kg/sec) for these tests. The coolant gas supply pressure to the test bearing ranged from 18.5 to 27.5 pounds per square inch absolute (127.5×10^3 to 189.5×10^3 N/sq m abs).

The 250-gallon (0.946 m^3) supply of liquid hydrogen provided enough coolant gas for a test-run time of approximately 2 hours after the cool-down period. A test series for a bearing consisted of approximately 10 hours running time. The test series was ended prematurely, however, when mechanical damage to the retainers had occurred.

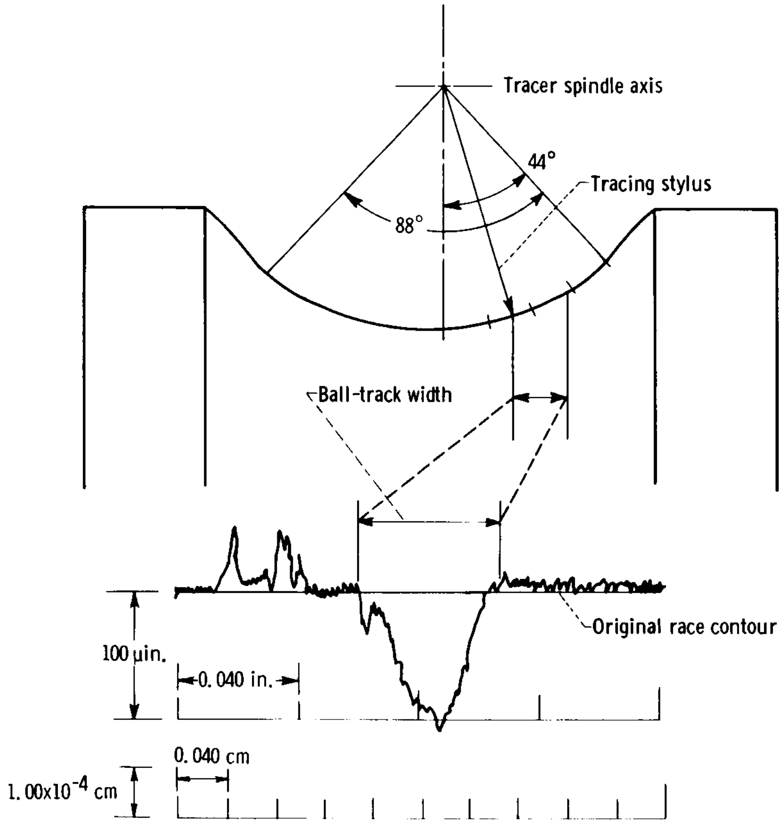
Post-Test Inspection of Bearings

After each test the system was purged with helium gas. The test bearing was (1) inspected for wear, (2) washed in trichloroethylene, (3) placed in a vacuum desiccator for approximately 6 hours, and (4) weighed to determine the weight loss or gain (in mg) of each component. Transverse surface profile traces were made on the inner- and outer-race grooves, in the region of the pretest profiles, to determine the extent of wear or film buildup from transferred retainer material. The balls, races, and retainers were examined visually and with optical microscopy to help determine the extent of wear and surface damage. Photographs of the retainers were made to illustrate the wear patterns and damage that occurred in the test period.

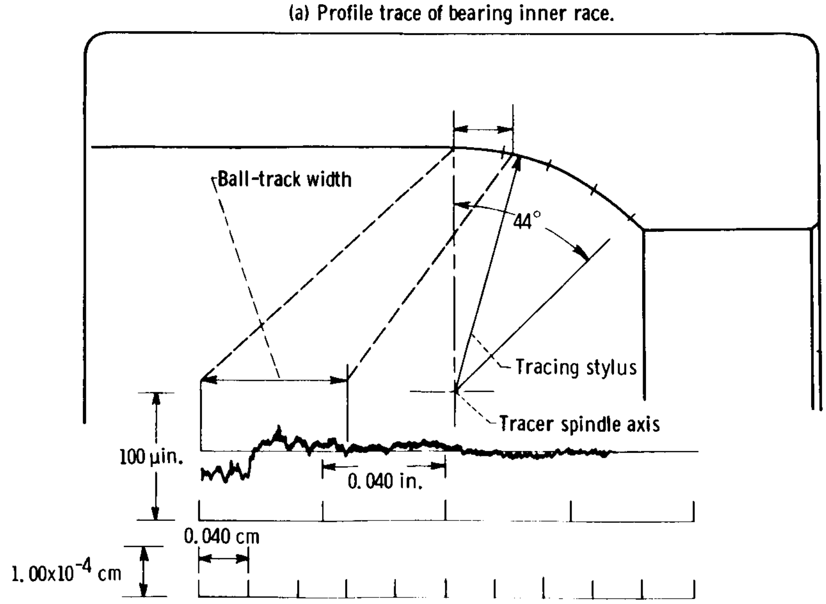
Surface Profile Traces

The profile traces were made with a rotary-piloted measuring instrument that incorporated a diamond-tipped tracing stylus with a 0.0005-inch (0.0013 cm) radius. As the stylus traced over the workpiece, it followed the surface irregularities. A highly magnified profile trace was produced and recorded on linear chart paper. The magnifications used in this investigation were 10 000 normal to the direction of stylus traverse and 25 in the direction of traverse. Typical profile traces are illustrated in figure 4: figure 4(a) is inner-race groove trace with an 88° traverse, and figure 4(b) is an outer-race groove trace with a 44° traverse. The horizontal line represents the original surface contour. The profile trace above this horizontal line is film transferred from the retainer material, and the profile below the line is race wear.

The computerized program for heat generation due to ball spin (ref. 2) indicated that outer-race control (ball spin at the inner race) prevails in 40-millimeter-bore ball bearings with the internal geometry given in table I (p. 7) at 20 000 rpm with a 200-pound (890 N) thrust load. The maximum Hertz stresses were 230 000 and 213 000 pounds per square inch (1.585×10^{9} and 1.465×10^{9} N/m^{2}) for the inner- and outer-race contacts, respectively. The inner race is therefore subjected to more severe operating conditions than the outer race. All profile traces were made on the inner-race grooves in the ball-track region for evaluation of the formation and life histories of the transfer films (see fig. 4(a)). Each successive profile trace of an inner-race groove was made in approximately the same location as the initial prerun trace.



(a) Profile trace of bearing inner race.



(b) Profile trace of outer race.

Figure 4. - Typical race groove traces showing film transfer and wear in ball-race contact areas. Retainer material, glass cloth with PTFE binder; speed, 20 000 rpm; thrust load, 200 pounds (890 N); coolant, hydrogen gas at 60° R (33° K); run time, 628 minutes.

TABLE II. - SUMMARY OF BEARING TEST RESULTS

[Test conditions: Shaft speed, 20 000 rpm; thrust load, 200 lb (890 N); coolant flow rate, 0.014 to 0.031 lb/sec (0.006 to 0.014 kg/sec) hydrogen gas at 60° R (33° K); maximum Hertz stress, 230 000 psi (1.585×10^{9} N/m^{2}) (inner race) and 213 000 psi (1.465×10^{9} N/m^{2}) (outer race).]

Retainer	Retainer material	Bearing	Total test time, min	Test time at 20 000 rpm, min	Retainer			Post-test bearing condition		
					Wear, weight percent	Sliding distance at inner race		Retainer	Inner race	Balls
						ft	m			
1	Laminated glass cloth with PTFE binder	13-S	628	545	0.18	3.33×10^{6}	1.02×10^{6}	Very good	Adhesive wear (fig. 13)	Scuff marks on wear track
		16-S	349	300	0.11	1.84×10^{6}	0.56×10^{6}	Delaminated (fig. 12(a))	Adhesive wear	Scuff marks on wear track
2	Glass-fiber - molybdenum disulfide-filled PTFE	14-S	615	518	0.19	3.19×10^{6}	0.97×10^{6}	Very good	Slight adhesive wear	Transfer film on wear track
		23-S	618	500	0.25	3.09×10^{6}	0.94×10^{6}	Very good	Wide wear track with transfer film	Dark, hammered effect over entire surface
3	Glass-fiber-filled PTFE	15-S	464	400	0.06	2.45×10^{6}	0.75×10^{6}	Cracked (fig. 12(b))	Adhesive wear with scuff marks	Scuff marks on wear track and adhesive wear
		22-S	580	500	0.17	3.04×10^{6}	0.93×10^{6}	Very good	Transfer film, no adhesive wear	Transfer film on wear track
4	Bronze-filled PTFE	20-S	575	500	0.16	3.07×10^{6}	0.94×10^{6}	Very good	Bronze-colored film, no adhesive wear	Bronze-colored film on wear track
		21-S	581	501	0.89	3.08×10^{6}	0.94×10^{6}	High wear	Heavier bronze-colored film than on 20-S	Heavier bronze-colored film than on 20-S
5	Copper composite	17-S	213	176	2.96	1.08×10^{6}	0.33×10^{6}	High wear (fig. 12(d))	Copper-colored film, slight adhesive wear	Copper-colored film over entire surface
6	Silver composite	11-S	138	120	----	0.73×10^{6}	0.22×10^{6}	Balls rubbed shroud (fig. 12(c))	Race not separable	Silver-colored film, some scuff marks
		18-S	234	200	3.53	1.216×10^{6}	0.37×10^{6}	High wear and cracked (fig. 12(e))	Silver-colored wear track with some adhesive wear	Silver-colored film
7	Molybdenum disulfide-filled polyimide	12-S	54	15	0.76	--------	--------	High wear	Wide, dark-colored wear track with adhesive wear	Dark film over entire surface with adhesive wear
		19-S	22	0	----	--------	--------	Destroyed (fig. 12(f))	Bearing seized	Bearing seized

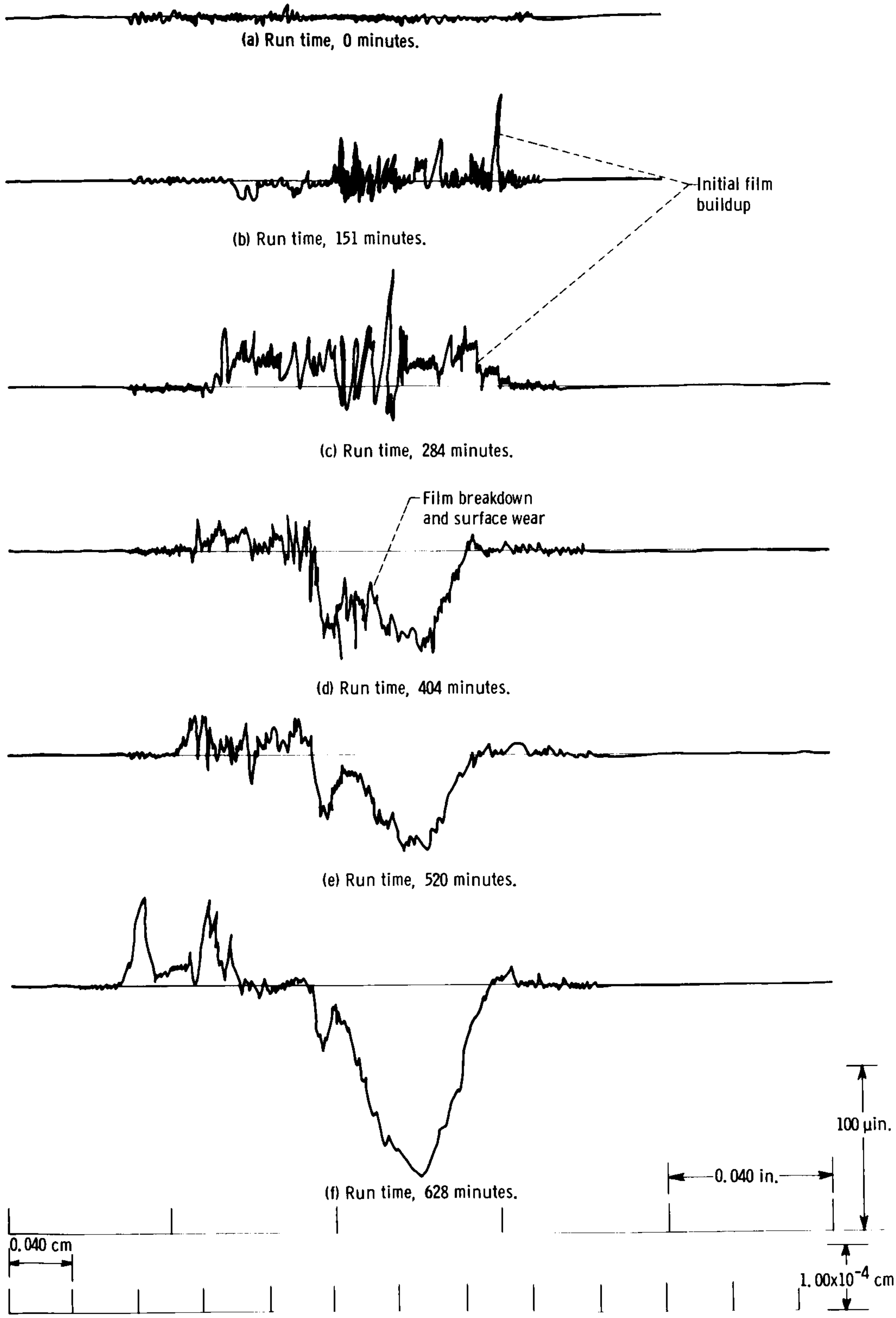


Figure 5. - Progressive profile traces of inner-race groove (normal to ball-rolling direction) of bearing 13-S. Retainer material, 38 percent glass cloth with 62 percent PTFE binder; shaft speed, 20 000 rpm; thrust load, 200 pounds (890 N); coolant, hydrogen gas at 60° R (33° K).

RESULTS AND DISCUSSION

Formation and Life History of Transfer Films on the Bearing Inner Races

[Results of the bearing tests are summarized in table II (p. 11).]

Laminated glass cloth with PTFE binder (38-percent glass cloth laminate, 62-percent PTFE binder). - Successive traces of the inner-race groove of bearing 13-S with this retainer material are shown in figure 5. After a 284-minute run time, a substantial film was established. The scratches that appear in the film are indicative of abrasion. Continued running resulted in film breakdown and inner-race surface wear (fig. 5(d)). Race wear progressed rapidly after the film had worn away, and at 628 minutes the wear depth was 115 micro inches (2.92×10^{-4} cm) (fig. 5(f)). At a point 180° from that of figure 5(f), the maximum wear depth was 210 micro-inches (5.33×10^{-4} cm). Continued operation with this adverse wear condition on the inner race would probably result in complete bearing failure.

The test series of bearing 16-S was terminated prematurely (after 349 min) because of delamination of the retainer material between adjacent ball pocket. The profile traces of the inner-race groove indicated a film thickness between 10 and 20 micro-inches (0.25×10^{-4} to 0.51×10^{-4} cm). This range is slightly less than the film thickness observed for bearing 13-S, which measured from 15 to 30 micro-inches (0.38×10^{-4} to 0.76×10^{-4} cm) after a 284-minute run (fig. 5(c)).

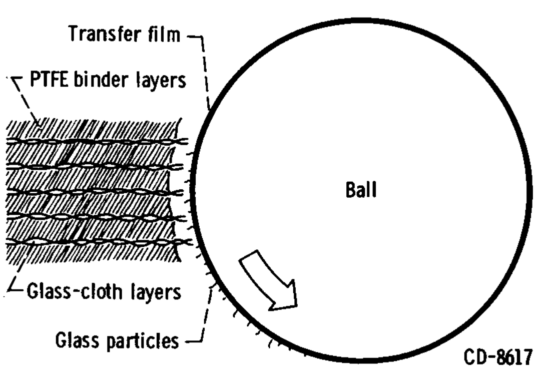


Figure 6. - Postulated wear process in ball pocket of glass-cloth with PTFE binder retainer.

The breakdown of the transfer film was probably caused by abrasive glass particles broken away from the glass cloth in the retainer ball pocket by the rubbing action of the ball. This postulated abrasive-wear process is illustrated in figure 6. The retainer material initially deposited by the balls on the race groove was probably composed largely of PTFE, which is the softer material. After a 284-minute run time, the PTFE between the glass-cloth layers had worn away, leaving the glass exposed to the rubbing action of the balls. With continued running the glass fibers shredded away from the cloth and adhered to the film on the ball. Since an appreciable amount of the material transferred to the race was now abrasive glass fibers, the deposited film was worn away faster than it could be reformed by the PTFE; consequently, heavy race groove wear resulted.

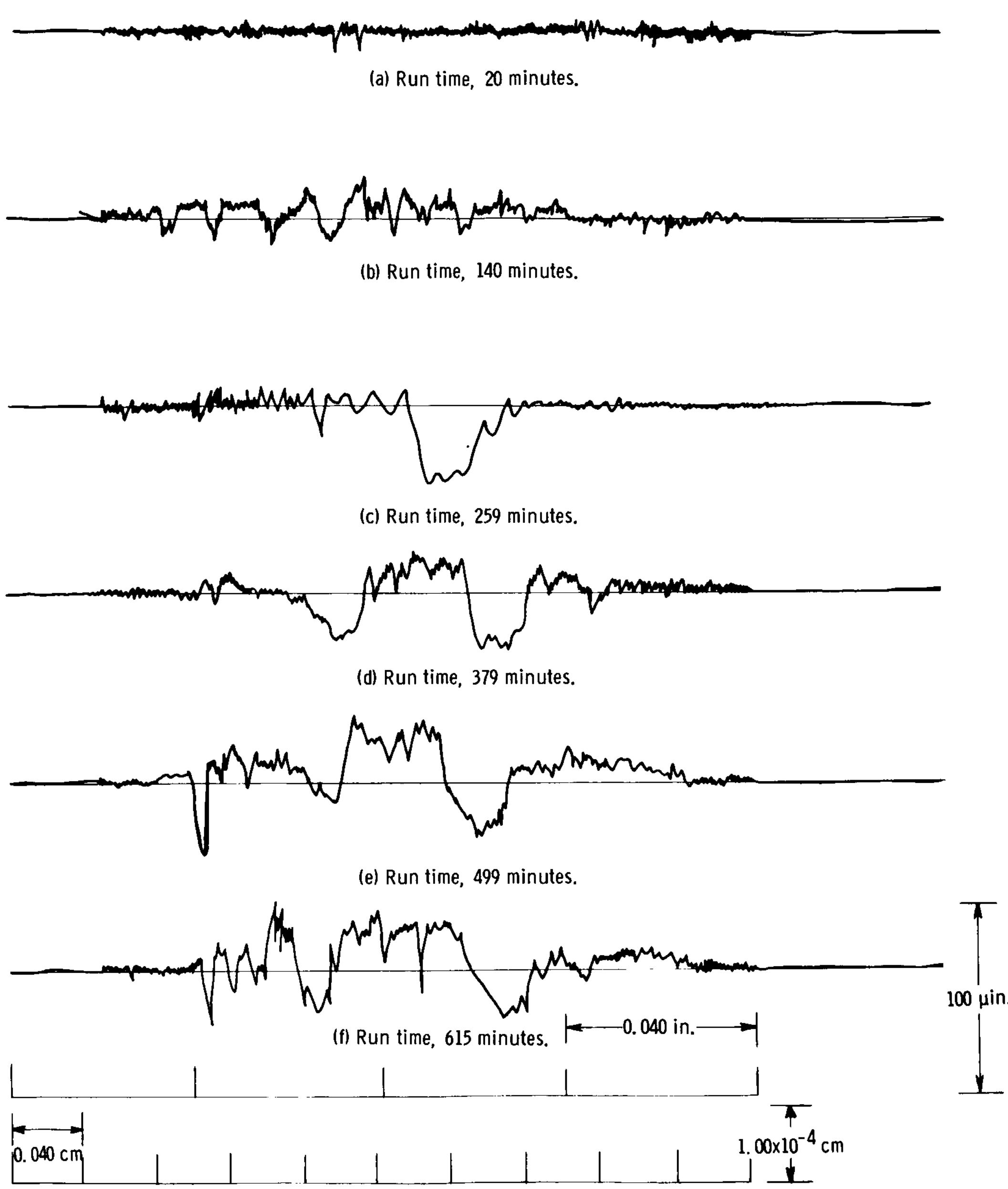


Figure 7. - Progressive profile traces of inner-race groove (normal to ball-rolling direction) of bearing 14-S. Retainer material, 15 percent glass fibers, 5 percent molybdenum disulfide, and 80 percent PTFE; shaft speed, 20 000 rpm; thrust load, 200 pounds (890 N); coolant, hydrogen gas at 60° R (33° K).

Glass-fiber - molybdenum disulfide-filled PTFE (15-percent glass fiber, 5-percent molybdenum disulfide, 80-percent PTFE). - Progressive profile traces of the inner race groove of bearing 14-S with a retainer fabricated from this material are presented in figure 7. The traces indicate a partial film distribution over the ball-track area. The maximum film thickness measured 35 micro-inches (0.89×10^{-4} cm) near the center of the ball track after a 499-minute run time (fig. 7(e)). Some abrasive wear occurred on both sides of the ball-track center. The maximum measured wear depth was 45 micro-inches (0.11×10^{-4} cm) and occurred after a 259-minute run. Further wear progression appeared to be inhibited by film reformation throughout the duration of the 10-hour run.

A wide film band covered approximately 50 percent of the inner-race groove profile of bearing 23-S. The film thickness measured approximately 20 micro-inches (0.50×10^{-4} cm) after a 149-minute run time. The film remained on the race groove for the entire 618 minutes of the test series (see table II, p. 11). Subsequent profile traces indicated that the inner-race groove of this bearing had not sustained any appreciable race wear. A discussion of the wide band of transfer film on this bearing will be presented in the section Post-Test Examination of Bearings.

Glass-fiber-filled PTFE (15-percent glass fiber, 85-percent PTFE). - This material exhibited excellent film transfer capabilities. The traces in figure 8 represent the film buildup on the inner-race groove of bearing 22-S. Similar traces were obtained with bearing 15-S, which was run with the same retainer material. Two prominent similarities of the surface films found on the two bearing inner-race wear tracks were (1) the uneven, scratched appearance of the film and (2) a film buildup of approximately 30 micro-inches (0.76×10^{-4} cm). Notable differences between the two inner-race profiles were the following: (1) the scratch marks of the film on bearing 22-S (fig. 8(f)) only penetrated to the surface of the race, whereas on bearing 15-S the scratch marks penetrated the surface of the race and were approximately 40 micro-inches (1.02×10^{-4} cm) deep; (2) no evidence of film buildup on bearing 22-S (fig. 8) is seen until after a 350-minute run time, whereas a thin film of about 10 micro-inches (0.25×10^{-4} cm) was deposited on bearing 15-S after a 120-minute run time.

Bronze-filled PTFE (30-percent bronze powder, 70-percent PTFE). - The bronze-filled PTFE material provided a film on the inner-race groove for the entire series of runs in the cold hydrogen-gas environment. The profiles illustrated in figure 9 for bearing 20-S are also typical of bearing 21-S. The film transferred to the inner-race surface is relatively thin in comparison with the three materials previously discussed; however, abrasive wear of the film or inner-race groove was not evident with this material.

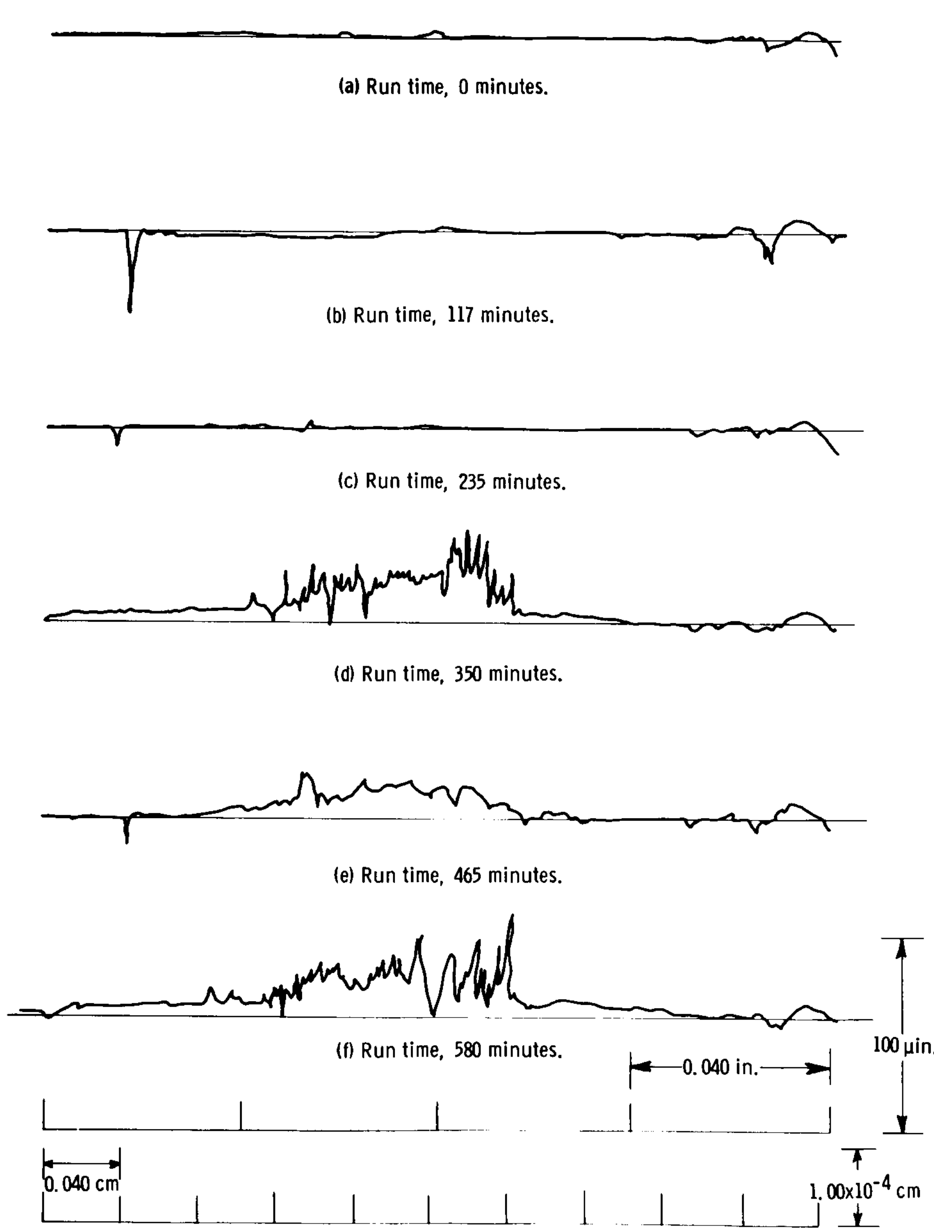


Figure 8. - Progressive profile traces of inner-race groove (normal to ball-rolling direction) of bearing 22-S. Retainer material, 15 percent glass fibers and 85 percent PTFE; shaft speed, 20 000 rpm; thrust load, 200 pounds (890 N); coolant, hydrogen gas at 60° R (33° K).

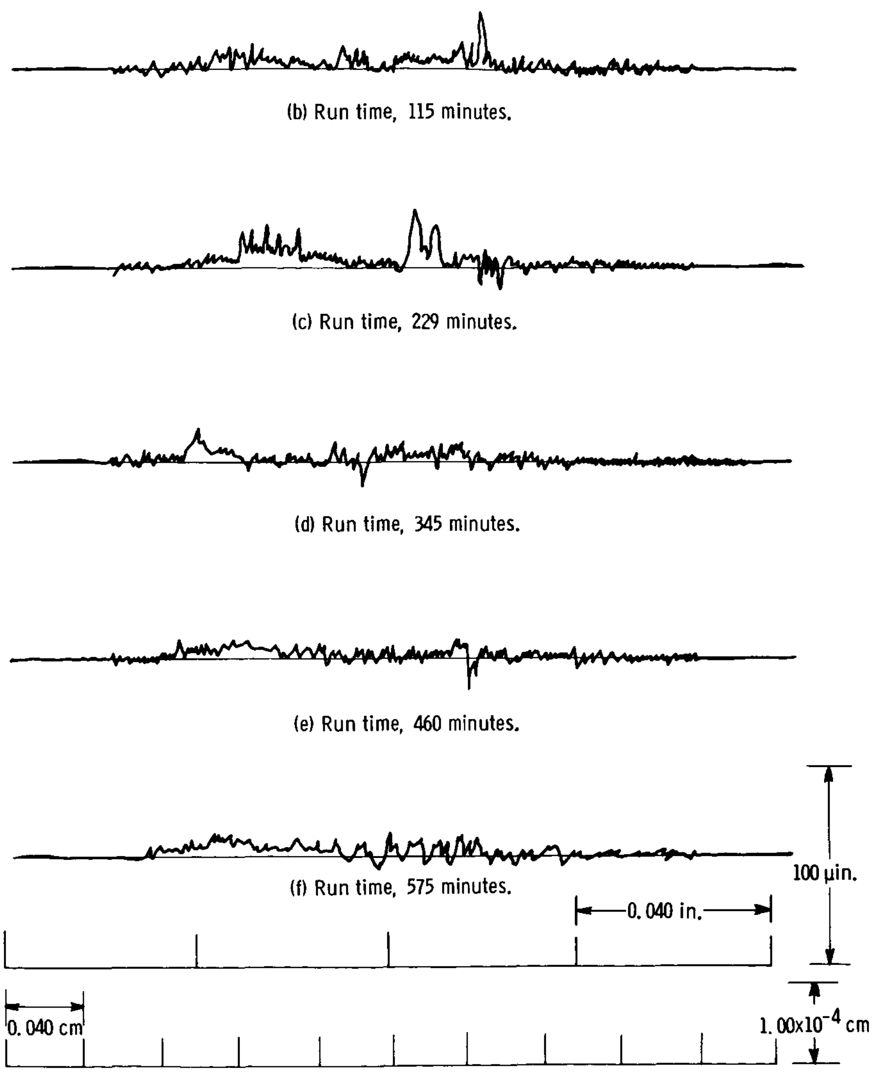


Figure 9. - Progressive profile traces of inner-race groove (normal to ball-rolling direction) of bearing 20-S. Retainer material, 30 percent bronze powder and 70 percent PTFE; shaft speed, 20 000 rpm; thrust load, 200 pounds (890 N); coolant, hydrogen gas at 60° R (33° K).

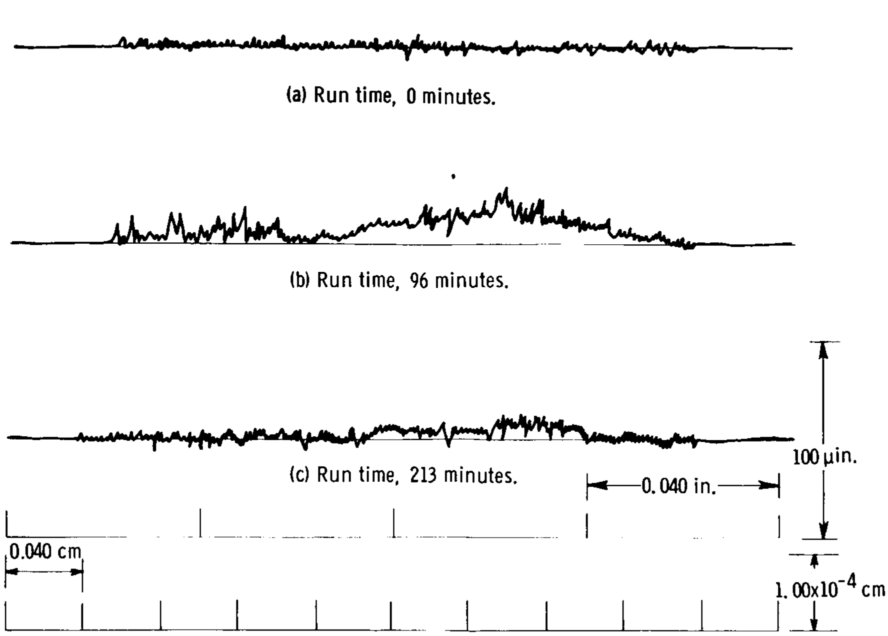


Figure 10. - Progressive profile traces of inner-race groove (normal to ball-rolling direction) of bearing 17-S. Retainer material, 78 percent copper, 9 percent PTFE, and 13 percent tungsten diselenide; shaft speed 20 000 rpm; thrust load, 200 pounds (890 N); coolant, hydrogen gas at 60° R (33° K).

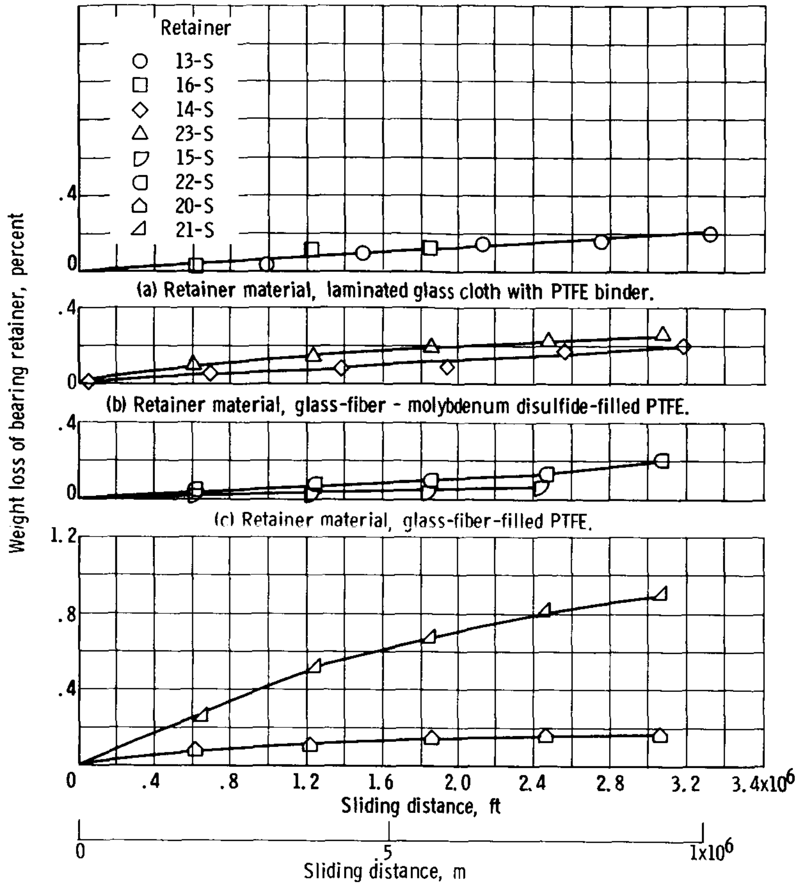
Copper composite (78-percent copper, 9-percent PTFE, 13-percent tungsten diselenide). - The copper composite proved to be a good lubricating material. It provided an adequate film on the inner-race groove (bearing 17-S), as shown in the profile traces of figure 10. A uniform copper-colored film deposited on the ball and outer-race groove was also observed. The run time of this material was termined at 213 minutes because of high retainer wear.

Silver composite (85-percent silver, 5-percent PTFE, 10-percent tungsten diselenide). - A profile of the inner race lubricated by the silver composite material (bearing 18-S, table II, p. 11) was made after a 117-minute run time. The deposited film was not thick enough to be measured; however, the balls and race grooves appeared to have a light, uniform, silver-colored coating on their surfaces. No subsequent traces were made because the retainer failed after a 234-minute run time. Profile traces of the inner race of bearing 11-S were not made, since the bearing could not be separated after the high retainer wear of the 138-minute run.

Molybdenum disulfide-filled polyimide (85-percent polyimide, 15-percent molybdenum disulfide). - Profile traces were not made on the inner races of bearings 12-S and 19-S, since both initial runs resulted in failure of the retainer.

Retainer Wear

The first four materials listed in table II exhibited the lowest wear of the seven



(d) Retainer material, bronze-filled PTFE.

Figure 11. - Bearing retainer weight loss as function of sliding distance relative to inner race. Retainer inner-diameter sliding velocity on inner race, 5720 feet per minute (29.1 m/sec); ball-rub velocity in retainer pocket, 4360 feet per minute (22.2 m/sec); shaft speed, 20 000 rpm; thrust load, 200 pounds (890 N); coolant, hydrogen gas at 60° R (33° K).

materials investigated. Percent weight loss for each of these four materials is plotted in figure 11 as a function of total sliding distance of the retainer inner diameter. (Sliding distance represents the relative distance that a reference point on the retainer inner diameter slides with respect to the inner-race contacting surface.) The maximum weight loss was 0.25 percent or less of the original retainer weight for each of the first four materials except with bearing 21-S, which will be discussed later.

Bearing 23-S, with a glass-fiber - molybdenum disulfide-filled PTFE retainer, initially had insufficient inner land clearance (see table I, p. 7). As the bearing was cooled to the cryogenic operating temperature, this lack of clearance brought the bearing to a complete stop from a speed of 5000 rpm with a 200-pound (890 N) applied load. In this initial run the retainer incurred a 0.61-weight-percent wear in a 20-minute run time. After machining the inner diameter to a 0.048-inch (0.122 cm) clearance with the inner-race land, the retainer wear rate (slope of wear as a function of distance) was similar to the wear rate of the other PTFE materials shown in figure 11. Greater-than-normal inner-land clearances are required for these PTFE retainers because of the large differential contraction between the bearing retainer and race materials.

The bronze-filled PTFE retainer of bearing 21-S had a weight loss of 0.89 percent for a 581-minute run time. This high wear value was attributed to the eccentric shape of the retainer, which rubbed heavily on the inner-race land where the inner diameter had minimum clearance (see table I, p. 7). It is evident from these results that in order to minimize retainer wear and ensure free bearing rotation at cryogenic temperatures the possibility of high loads on the retainer wearing surfaces must be reduced. This can be accomplished by provision of optimum initial clearances and concentric surfaces between the retainer and the race land.

The copper (bearing 17-S) and silver (bearing 18-S) composite materials demonstrated the relatively high wear of 2.96-percent (after 213 min) and 3.53-percent (after 234 min) weight loss, respectively. It is speculated that the excessive wear values of these two materials contributed to the early failures of the retainers.

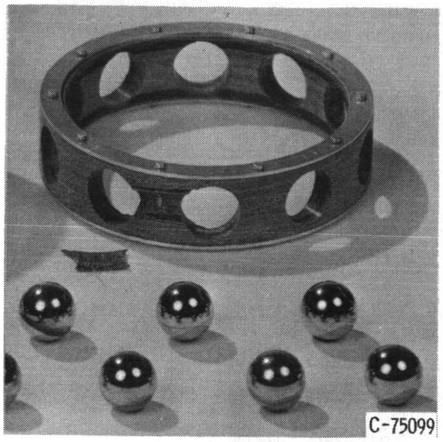
The molybdenum disulfide-filled polyimide retainer of bearing 12-S had a wear value of 0.76-weight-percent for the relatively short life of 54 minutes. The run with this bearing was terminated due to indications of failure by a rapid rise in outer-race temperature.

Mechanical Damage of Bearing Retainers

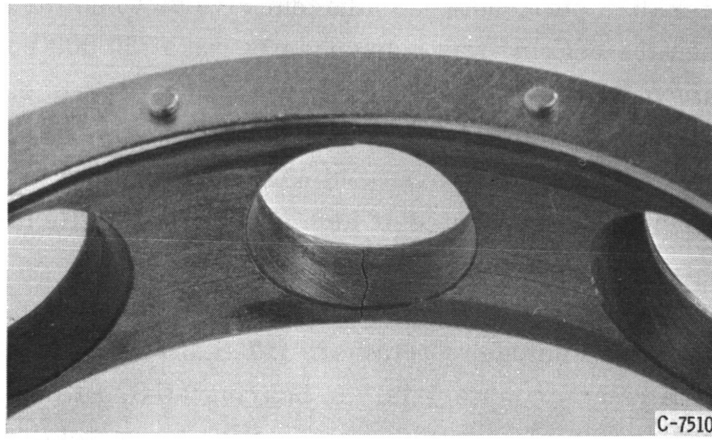
Seven of the thirteen test series in the program were terminated prematurely because of mechanical damage to the bearing retainers (table II, p. 11). Mechanical damage resulted from either (1) structural deficiency of the material, (2) improper retainer design, or (3) high wear of the material.

Laminated glass cloth with PTFE binder. - After a 349-minute run, the retainer of bearing 16-S delaminated between two ball pockets on the outer diameter of the retainer (fig. 12(a)). The laminate separation was initiated at either the rivet hole or at the ball-pocket wall. Delamination probably resulted from insufficient PTFE binder between adjacent glass-cloth layers or an improper curing technique in the laminating process. Laminate separation of this material was also experienced in bearing retainers run in liquid oxygen (ref. 2) and liquid hydrogen (refs. 3 and 4).

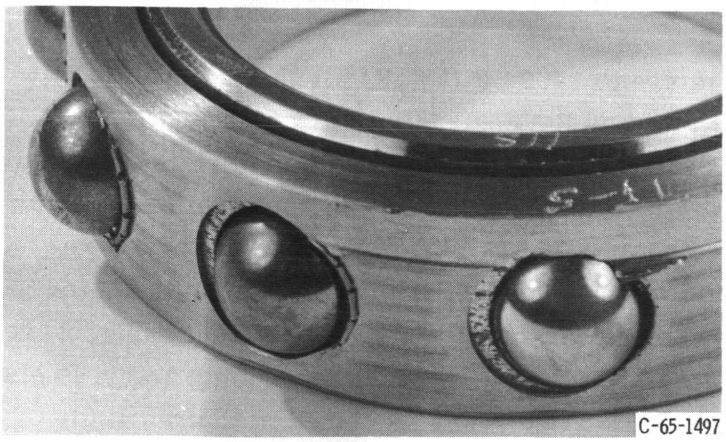
Glass-fiber-filled PTFE. - Two cracks 180° apart appeared in a ball pocket of bearing 15-S after a 464-minute run time. The aluminum-shrouded retainer cracked at the narrow section of the ball-pocket web as shown in figure 12(b). The thermal contraction (shrinkage) of glass-fiber-filled PTFE from room temperature to -400° F (33° K) is more than twice that of aluminum. It is speculated that this difference in shrinkage caused the retainer body to shrink away from the aluminum shroud at the



(a) Laminated glass cloth with PTFE binder (bearing 16-S). Delamination after 349 minutes.



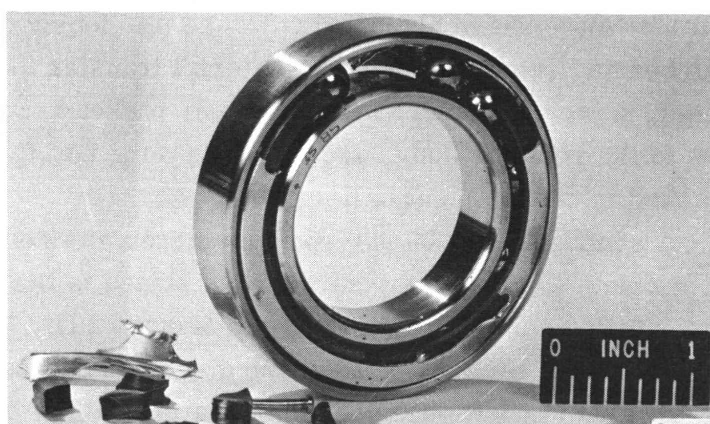
(b) Glass-fiber-filled PTFE (bearing 15-S). Cracks in ball pocket after 464 minutes.



(c) Silver composite (bearing 11-S). Shroud rubbed on outer-race land and moved relative to body; ball wore into shroud; bearing jammed after 138 minutes.

(d) Copper composite (bearing 17-S). Shroud rubbed on outer-race land; high wear after 213 minutes.

(e) Silver composite (bearing 18-S). Shroud rubbed on outer-race land; ball pocket cracked after 234 minutes.



(f) Molybdenum disulfide-filled polyimide (bearing 19-S). Complete failure after 22 minutes.

Figure 12. - Mechanical damage of bearing retainers. Shaft speed, 20 000 rpm (2100 rad/sec); thrust load, 200 pounds (91 kg); coolant, hydrogen gas at 60° R (33° K).

outer diameter, between adjacent rivets, when the bearing was cooled to -400° F (33° K). When the bearing was subsequently run at 20 000 rpm, the centrifugal growth of the glass-filled PTFE between the restraining rivets caused fracture in the material at the thin web sections of the ball pocket. Cracking at the thin sections of the retainer ball pockets was also experienced with this material in several preliminary runs when the bearings were operated at high speeds (1.6 million DN value and above) in cold hydrogen gas.

Copper and silver composites. - The series of runs of bearings equipped with copper and silver composite retainers (17-S and 18-S) were terminated because of the high wear of the retainer materials. In bearing 11-S, fitted with a silver composite retainer, the stainless-steel shroud moved relative to the retainer body, and the balls wore into the shroud and jammed the bearing (fig. 12(c)). Pinning the retainer in two places, 180° apart, prevented relative movement between the shrouds and retainer bodies of bearings 17-S and 18-S.

The contraction from room temperature to -400° F (33° K) for the copper and silver composite materials is probably not as great as the contraction for other PTFE-containing materials. The inner-land clearances for the composite materials specified in table I (p. 7) would therefore be larger than are required. The combination of larger-than-required inner-land clearances and poor wear resistance in these materials resulted in an unbalanced running condition and caused the retainers to rub on the outer-race land. It is assumed that friction on the outer-race land was the direct cause of the shroud movement and the subsequent failure of bearing 11-S. This rubbing action is also evident on the retainer shrouds of bearings 17-S and 18-S, as shown in figures 12(d) and (e), respectively. In bearing 18-S the retainer also cracked through one ball pocket.

Molybdenum disulfide-filled polyimide. - The poor wear results obtained with this retainer material in bearing 12-S were previously discussed. Post-test examination of this bearing revealed adequate material transfer to the balls and race grooves; the retainer, however, experienced high ball-pocket wear. The aluminum shroud moved relative to the retainer body, and the balls wore into the shroud. The retainer body also cracked in two adjacent ball pockets.

A shaft speed of 20 000 rpm was never attained for bearing 19-S as it failed in 22 minutes. Although the shroud was pinned to the retainer body in two places, the retainer failed completely as shown in figure 12(f). This material has shown little promise as a candidate for cryogenic bearing service because of its brittleness and poor mechanical strength at low operating temperatures. The dark appearance of the balls and race grooves indicated that the polyimide composition provided a lubricant film. Further evaluation of the film-transfer capabilities are rather futile, however, until the mechanical properties of this material can be substantially improved.

Post-Test Examination of Bearings

At the end of the test series, each bearing was examined under a microscope at a magnification of 15 to determine the extent of wear or surface damage on the ball and race wear tracks. A brief description of the apparent post-test condition of the inner-race and ball surfaces is given in table II (p. 11).

Adhesive wear was evident on most of the inner-race wear tracks and on several ball wear tracks. Adhesive wear may be defined as the most fundamental type of wear which occurs whenever two solid surfaces are in sliding contact, whether lubricated or not, and remains when all other types of wear are eliminated (ref. 7). When two clean metal surfaces come into intimate contact, welding occurs at the tips of the asperities. As one surface moves relative to the other, the welded junctions are broken, metal is plucked out, and the surfaces are left with a pock-marked appearance. Under the test conditions in this investigation, adhesive wear probably occurred on the inner-race and ball wear tracks after the initial oxide films had worn away but before a continuous lubricant film was established from transferred retainer material. A representative example of adhesive wear occurred on the inner race of bearing 13-S and is illustrated in figure 13.

The film, present on the inner-race and ball wear tracks, was composed primarily

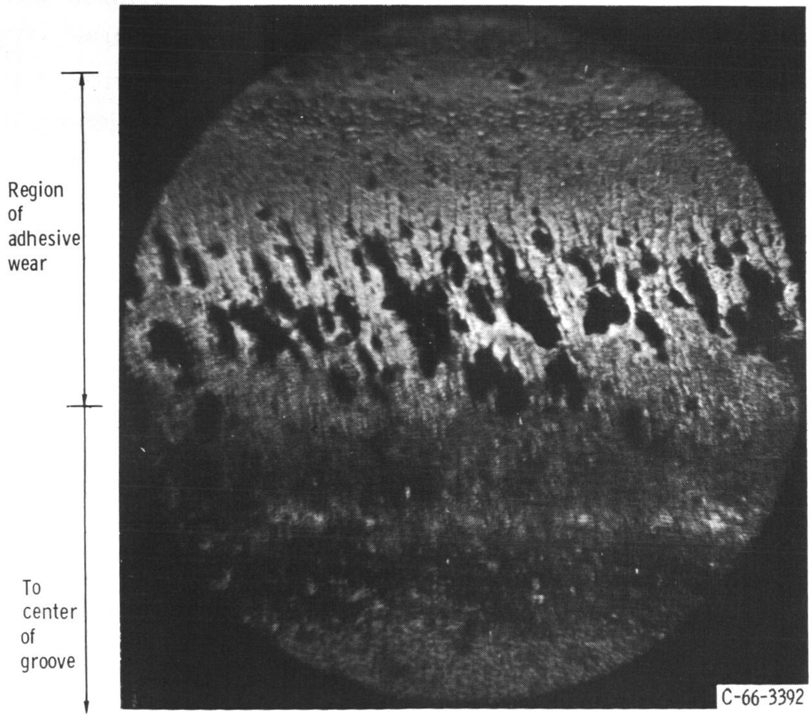


Figure 13. - Adhesive wear on inner-race wear track of bearing 13-S after 628-minute run time. Retainer material, 38 percent glass cloth and 62 percent PTFE binder; shaft speed, 20 000 rpm; thrust load, 200 pounds (890 N); coolant, hydrogen gas at 60° R (33° K). X75.

of transferred retainer material. This was verified by a bronze-colored wear track with the bronze-filled PTFE retainer (bearings 20-S and 21-S), and copper- or silver-colored tracks with the copper composite (bearing 17-S) or silver composite (bearings 11-S and 18-S) retainers. Rust-colored spots observed on the transferred film after exposure to air were probably metallic wear debris from the bearing balls and races.

The balls of bearing 12-S, with a molybdenum disulfide-filled polyimide retainer, were covered with a dark film, and the wear tracks appeared as bands in which adhesive wear had occurred. Scuffed areas appeared on the wear tracks of several balls of bearings 13-S, 16-S, and 15-S. These bearings were equipped with either glass cloth with PTFE binder or glass-filled PTFE retainers, and the scuffing probably resulted from abrasion by glass particles worn away from the retainer material. In bearing 11-S, with a silver composite retainer, scuffing was caused by ball contact with the shroud. The balls of bearing 23-S, with a glass-fiber - molybdenum disulfide-filled PTFE retainer, were dark colored and had a hammered appearance over their entire surface. In addition to an adverse ball surface condition, the inner race had a wide wear track, which is indicative of radial clearance loss for the bearing. Seizure with bearing 23-S because of insufficient retainer clearance was previously indicated in the section on retainer wear.

Several bearings showed no signs of distress on the inner-race or ball wear tracks. No adhesive wear or scuffed areas appeared on bearing 22-S equipped with a glass-fiber-filled PTFE retainer, or on bearings 20-S and 21-S with bronze-filled PTFE retainers. These bearings maintained a film on the inner-race wear tracks without evidence of race wear, and also had a low value of retainer wear for the entire series of test runs (see fig. 11, p. 19).

SUMMARY OF RESULTS

Seven self-lubricating materials were evaluated as retainers in 40-millimeter-bore ball bearings running in hydrogen gas at 60° R (33° K). These materials were the following: (1) laminated glass cloth with PTFE binder, (2) glass-fiber - molybdenum disulfide-filled PTFE, (3) glass-fiber-filled PTFE, (4) bronze-filled PTFE, (5) copper - PTFE - tungsten diselenide composite, (6) silver - PTFE - tungsten diselenide composite, and (7) molybdenum disulfide-filled polyimide. The bearings were operated at 20 000 rpm with a 200-pound (890 N) thrust load for periods up to 10 hours. The film-transfer characteristics and wear resistance of the retainer materials were determined by highly magnified surface profile traces, visual observations, and weight differential measurements of the bearing components. The following results were obtained:

1. Evidence of the formation, buildup, and wear of transfer films supplied by the retainer materials was provided by profile traces of the bearing inner-race wear tracks.

2. The glass-fiber-filled PTFE and the bronze-filled PTFE materials maintained a transfer film on the inner-race wear track for the entire test duration, and thereby prevented any inner-race wear.

3. The percent weight loss (wear) for the filled PTFE materials and the laminated glass-cloth PTFE material was approximately the same low value (less than 0.25 percent).

4. The metal composite materials demonstrated adequate film-transfer properties but extremely high wear in this application.

5. A fractured condition, accompanied by high wear, indicated that the strength properties and design of the molybdenum disulfide-filled polyimide retainers were inadequate for cryogenic applications.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 28, 1966,
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